

# STABILITY ANALYSIS ON ANCHOR-GROUND SYSTEM OF SUSPENSION BRIDGE ON SHANGHAI SOFT GROUND

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## 1. INTRODUCTION

Shanghai, the biggest city of China, is one of the rapidly developing cities in China. In recent years, the construction of large scale infrastructures of the city is developing rapidly. Now, a traffic engineering of outer ring expressway project (OREP) is being constructed in Shanghai. There are two Huangpu river-cross projects of the OREP. One of the options of river-cross projects is large span suspension bridge. The stable and economical anchor is the technical key when a large span suspension bridge is built on Shanghai Quaternary stratified deposits. There are some detrimental factors such as high sensitivity, low shear strength, large compression and rheological properties when an anchor is built on Shanghai saturated soft ground.

The anchor of suspension bridge is a structure that endures large tension forces from the bridge cables. When it is pulled by the cables, except for satisfying the stability of sliding and overturning of anchor itself, the ground movement under long-term tension forces is also a significant problem in design of suspension bridge. It is known that under immediate loading ground will deform elastically or elastoplastically. Under long term loading, when the stress level in ground exceeds a limitation, deformation is time-dependent and will increase with time, that is,  $\varepsilon=f(t)$ , so-called rheological behaviour of soft clay. In order to ensure the long-term

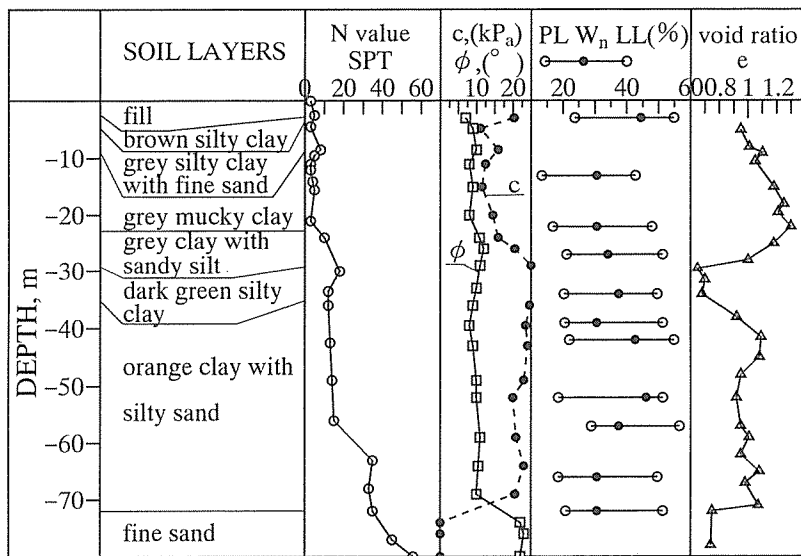


Fig. 1 Geological profiles

stability and reliability of the anchors on soft ground, the tensile force from cable should be effectively transferred into deeper ground and the time-dependent deformation should be limited within converging range. Therefore, the aspects of this problem should be studied as followings: the structure type of anchor should be reasonably selected, the depth and size of the anchor should be optimized; the soft ground should be improved effectively and reliable construction scheme should be decided.

This paper first proposes the possible structure types with reasonable size and construction methods. Furthermore, the stress and displacement in anchor and soil system (AGS) are analyzed by using a visco-elastic FEM program (Sun et al., 1981, 1988) so as to master the distribution law of stress and displacement in AGS partial quantitatively and/or qualitatively. Finally, by the results of the analysis, a reliable structure option of the anchor is determined.

## 2. GEOLOGICAL PROFILE AT BRIDGE SITE

The upper soil layers in Shanghai soft ground are the deltaic stratified deposits, in which the fourth layer is mucky clay with distinctive rheological properties. The geotechnical details of the ground at bridge site are shown in Figure 1.

## 3. POSSIBLE STRUCTURE TYPES OF THE ANCHOR

In the feasibility study of OREP (Shen et al., 1994), one of the options of river-cross projects is a suspension bridge with main span 800m, rise 80m and rise to span ratio is 1/10. The width of bridge deck is 8 lanes and the distance between cables is 32.15m. The maximum tension force in the two suspended cables is 300, 400kN, in which horizontal force is 270,000kN and vertical force is 131,700kN. The angle between cable and horizontal direction is  $26^\circ$  at the point of cable-anchor joint.

The anchor of suspension bridge is mainly used to endure the vast tension forces from the suspended cables and transfers them into surrounding ground. The anchors together with the towers are the significant supports of cables. Generally, the anchor is combined by foundation, anchoring block, anchoring stand and fixing device etc. The anchor structures introduced in following section are gravitational types, that is, the stability of anchor is balanced by its own gravity and the resistance of ground. In this paper's study, following three types of anchor structures are considered:

(1) Frictional dragging board anchor: This is a wing-like concrete structure. It is estimated that the length of the anchor alone the bridge is 57m. Width cross the bridge is 46.6m. Two access piers are directly put on the anchor to increase the balance force. The angle of the bottom of anchoring block with horizontal direction is  $26^\circ$ . Because the anchor is put on ground obliquely, the front of the anchor is on surface level, the rear is in underground with depth about 30.5m setting on ground layer of dark green silty clay.

(2) Shallow foundation anchor: This is a gravitational structure with length of 48.0m, width of 42.1m, bottom depth of 6m and top height of 28.5m over ground surface. In order to increase the balance force, two access piers are directly put on the anchor. The anchor is set on piles. Piles are set on ground layer of dark green silty clay. This option needs shallow excavation.

(3) Deep diagram wall gravitational anchor: There are two kind of diagram wall: the one is rectangular diagram wall with size of  $48 \times 54$ m; the other is circle diagram wall with the diameter of 60m. The thickness of the wall is 0.8m, wall depth is 32.2m and the excavation depth is 21m.

#### 4. FEM ANALYSIS ON ANCHOR-GROUND SYSTEM (AGS)

Fig.2 shows the FEM analytical pattern of anchor and ground system (AGS). The shaded area in the figure is improved zone. There are four options of AGS used in the analysis: option (1) is the shallow foundation on unimproved ground; option (2) is the shallow foundation on improved ground; option (3) is the deep foundation on unimproved ground; option (4) is the deep foundation on improved ground. In the calculation the anchor is treated as an elastic mass. Parameters used in the analysis are tabulated in Table 1.

##### Stress in AGS

Fig.3(a) and Fig.3(b) show the contour of octahedral shear stress in shallow foundation (option (1)) with ground unimproved and improved respectively.

Fig.3(c) and Fig.3(d) show the contour of octahedral shear stress in deep foundation (option (3) (4)) with ground unimproved and improved respectively.

The octahedral shear stress  $\tau_{\text{oct}}$  is the symbol of stress level in ground. The density of contour indicates not only the magnitude of shear stress but also the oscillation grade of stress. The denser the contour, the greater the stress changes and vice versa.

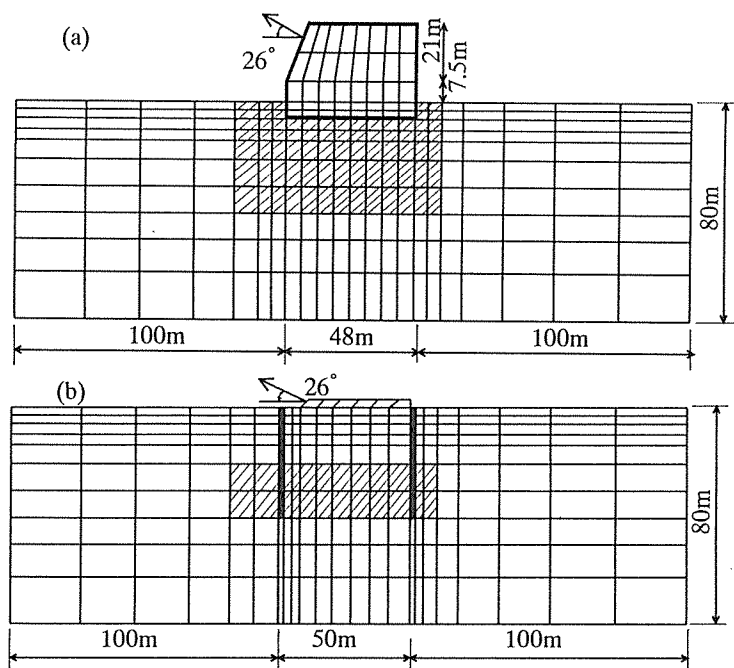


Fig. 2 FEM analysis pattern  
(a) shallow foundation (b) deep foundation

Table 1 Parameters of materials in analysis

Name of ground layer	thickness (m)	$\gamma, (\text{kN/m}^3)$	$E, (\text{kPa})$	$\nu$	$C (\text{kPa})$	$\phi, (^{\circ})$
Fills	3.0	18.0	4000	0.4		7.0
Grey mucky clay	18.0	18.0	2000	0.45	9.0	12.0
Brown silty clay	2.0	18.3	12000	0.40	10.0	13.0
Dark green silty clay	39.0	19.8	20000	0.35	14.0	22.0
Improved soils		21.0	50000	0.28	25.0	27.0
Anchor body		18.0	$2.1 \times 10^7$	0.16		

For shallow foundation, unimproved ground, under bottom of anchor with 10m and lateral two side of 6m, there is stress concentration and stress level is high. In other place, stress changes gradually. Around the anchor, the gray mucky clay reaches the critical state.

For shallow foundation, improved ground, stress concentration near anchor transfers to unimproved ground. Therefore, we can confirm that ground improvement of shallow foundation is very effective.

For deep foundation anchor, even there is no ground improvement, stress level is much lower than that in shallow foundation. Stress concentration is not so seriously. Stress level in mucky clay is very low. The layer with high stress concentration and high stress level is deep dark green silty clay. This layer is with high strength and it is a good bearing layer in Shanghai soft ground.

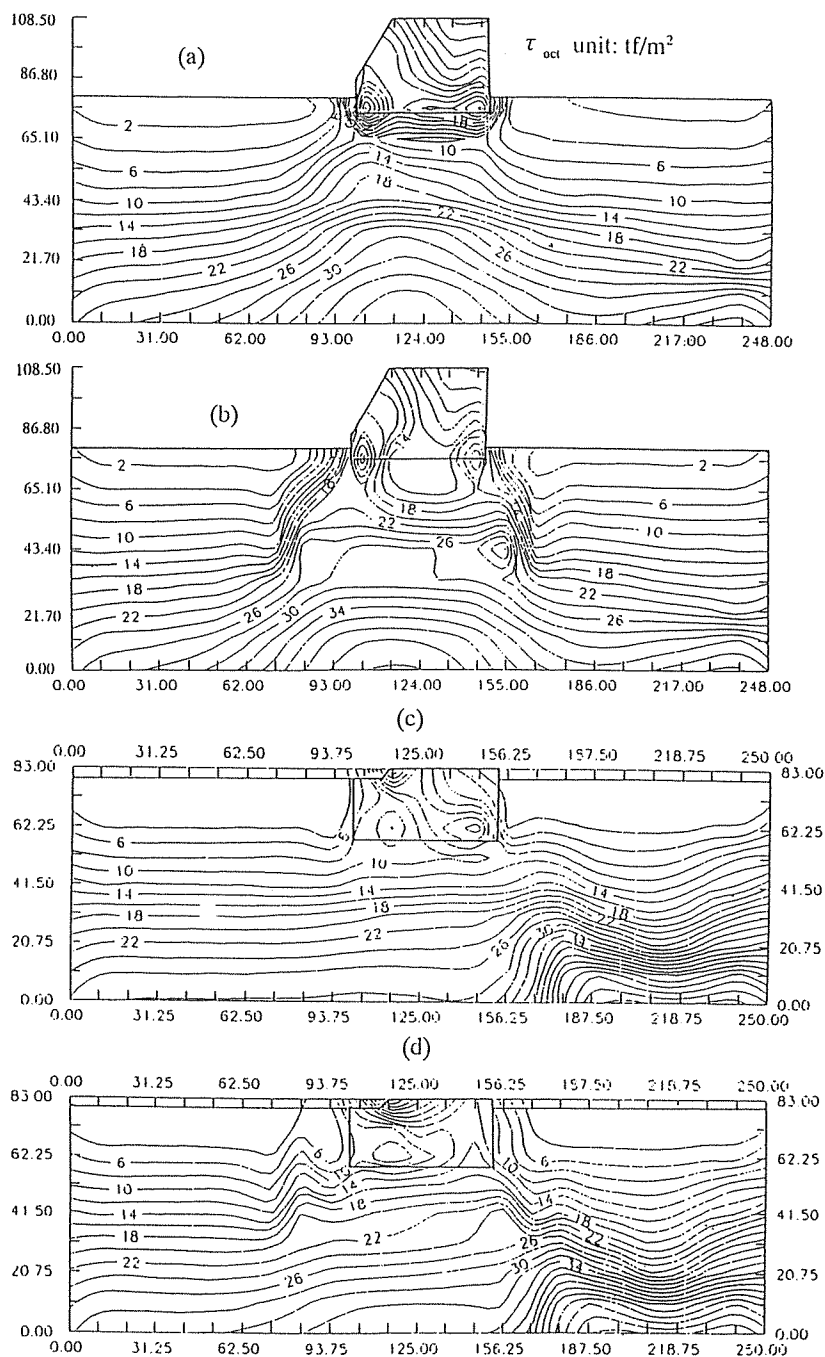


Fig. 3 Calculated contour of octahedral shear stress  
 (a) shallow foundation on unimproved ground  
 (b) shallow foundation on improved ground  
 (c) deep foundation on unimproved ground  
 (d) deep foundation on improved ground

For deep foundation anchor, improved ground, stress level is almost same as that in the unimproved deep foundation. The stress concentration transfers to upper layers. This is because of the improved ground with high stiffness. Therefore, from stress analysis, it is known that the improvement effect of deep foundation is not so evidently.

Of all above, we can conclude that deep foundation is better than shallow foundation.

### Displacement of AGS

Fig.4 shows the calculated displacement of different options (shallow and deep foundation with ground improved and unimproved).

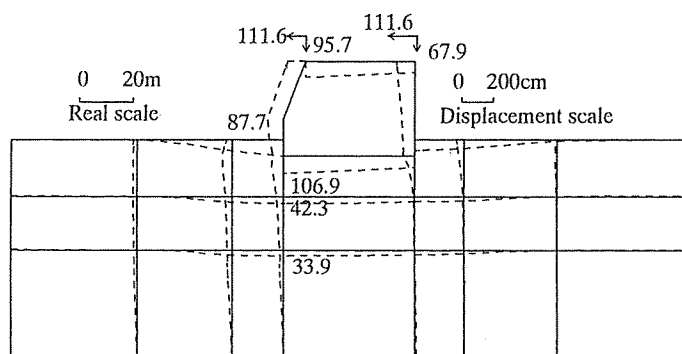
For the unimproved shallow foundation, displacement of anchor and ground is very large. The vertical displacements are settlement; the maximum settlement of anchor is about 106cm. Even in the layer of dark green silty clay at depth 39m, there is also 42cm settlement. The maximum horizontal displacement is about 111cm. The anchor structure has a body rotation tendency. This is because tension of the cables has an eccentricity. This indicates that option (1) is impossible.

For the improved shallow foundation-option (2). From Fig.4, the vertical displacements are much less than those of unimproved ground. Anchor's maximum settlement decreases from 106cm to 46.9cm. In other place displacements also decrease about 30~60%. The lateral displacements also decrease largely. This indicates that the ground improvement is very effective. However, option (2) also has a body rotation. The displacements are little larger than what are permitted by bridge cables.

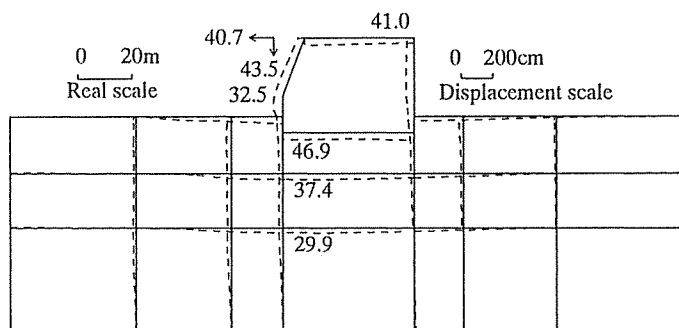
For option (3)-unimproved deep foundation, the calculated vertical displacements of anchor are uplift. The soft ground displacements are very small; the maximum is 10cm. The reasons of uplift are: the one is the tension force of cables; the other is compensation effect of deep foundation. The maximum vertical displacement of anchor is 51cm. This is because the load of piers which are put on anchor is not considered in the calculation. The maximum horizontal displacement of anchor is 26.1cm. The lateral displacements of ground are much less. There is also a body rotation of anchor, but it is much less and much better than that in shallow foundation.

For option (4)-improved deep foundation, the ground improvement is very efficacy for decreasing the displacements. The maximum vertical displacement reduces from 51cm to 19.8cm. The maximum lateral displacement is only 11cm. In the point of cable-anchor connection, displacement is only 9cm. The displacement already satisfies the permitted value stipulated in the design code of suspension bridge.

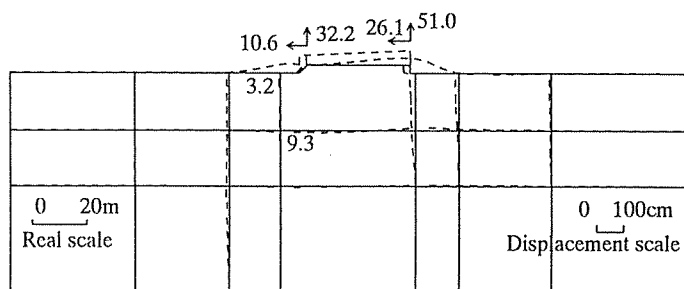
In the light of the calculated displacement, The deep foundation option is much better than shallow foundation.



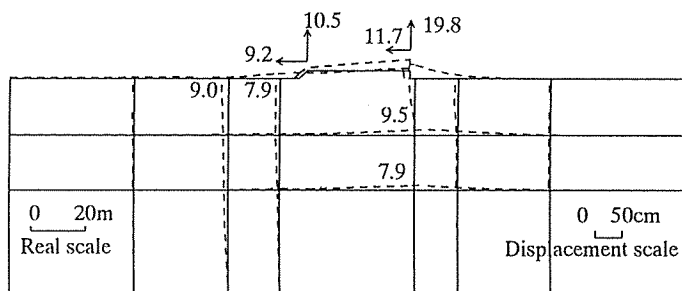
(a) shallow foundation on unimproved ground



(b) shallow foundation on improved ground



(c) deep foundation on unimproved ground



(d) deep foundation on improved ground

Fig. 4 Calculated nodal displacement

# 5. DISCUSSIONS OF THE ANALYTICAL RESULTS

Rheological behavior of soil is that when soil is under a long term loading, esp. when the stress level is over its rheological lower limits, the deformation (or strain) of soil will be continuing to develop with time. This strain sometimes maybe divergence, but under some condition, it can be convergence. As stated before, on the stabilization of suspension bridge's anchor on Shanghai soft ground, the rheological properties of soft clay is worth to be studied deeply. Fig.5 shows the tested creep properties of two sets of mucky clay samples by triaxial creep test (Sun, 1991). There are some creep regulars of Shanghai mucky clay as followings.

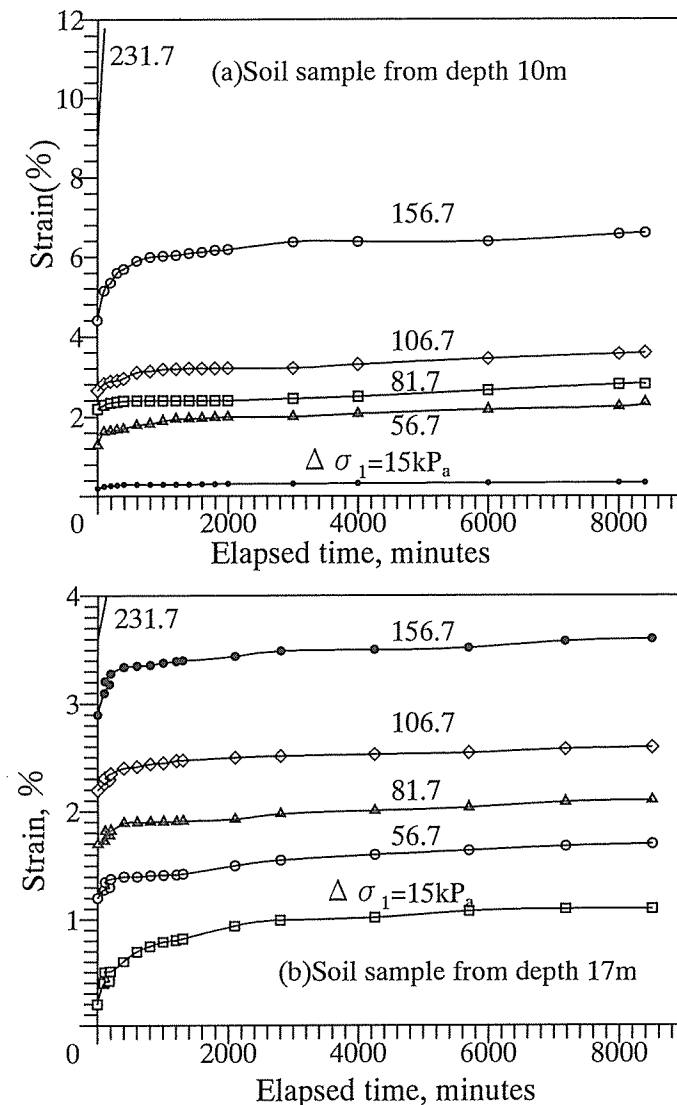


Fig. 5 Greep property of mucky clay  
(Triaxial test, After Sun, 1991)



Table 2 Calculated maximum increment of shear stress

Name of ground layer	options and $\Delta\tau_{oct}$ , kPa			
	(1)	(2)	(3)	(4)
Grey mucky clay	161.6	113.1	33.1	33.3
Brown silty clay	8.8	5.3	102.0	64.2
Dark green silty clay	54	1.0	125.4	14.5
Dark green silty clay			211.1	212.1

(1) When stress level is very low, the increase of the deformation of soft clay (esp. saturated mucky clay) with time is evident. However, only through a short period of time, the deformation will be stable.

(2) When stress level is not so high, that is,  $\sigma_{s1} < \sigma < \sigma_{s2}$ , creep strain will be attenuating and converging.

(3) When  $\sigma > \sigma_{s2}$ , strain is developing stably, that is,  $\frac{d\varepsilon}{dt} = A$ , so-called stable creep.

(4) When  $\sigma = \sigma_p$ , creep strain is developed promptly. This period from the beginning to the end is very short, only lasts several minutes or several ten minutes.

$\sigma_{s1}$ ,  $\sigma_p$ ,  $\sigma_{s2}$  are three critical state stress states of creep properties and their values relate with soil property and its depth. From creep property test of Shanghai clay: for mucky clay,  $\sigma_{s1} = 10 \sim 20 \text{ kPa}$ ,  $\sigma_{s2} = 30 \sim 100 \text{ kPa}$ ; for brown silty clay, creep behavior is not same as the mucky clay and the values of  $\sigma_{s1}$ ,  $\sigma_{s2}$  are a little higher than those of mucky clay; for dark green silty clay, creep property is not evidence and almost can be neglected. Of course, except for creep, rheological behaviors of soft clay also include stress relaxation, long term strength, elastic after effect, hysteresis effect and visco-plastic deformation etc. However, for the stability of anchor, the creep behavior of soft clay is the most important. By using Fig.5, the long-term stability of AGS with creep is discussed as followings.

In Fig.5, the stress level is expressed by stress increment  $\Delta\sigma_1$ . The stress should be alternated to octahedral shear stress  $\tau_{oct}$ :

$$\tau_{oct} = \frac{1}{3} \cdot \sqrt{[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6 \cdot (\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)]} = \frac{1}{3} \cdot \sqrt{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} \cdots (1)$$

When  $\sigma_2 = \sigma_3$ , then  $\tau_{oct} = \sqrt{2} \cdot (\sigma_1 - \sigma_2) / 3$ . In the triaxial test  $\sigma_2 = \sigma_3 = \text{constant}$  and  $\sigma_1$  was given an increment of  $\Delta\sigma_1$ . Then  $\tau'_{oct} = \sqrt{2} \cdot (\sigma_1 + \Delta\sigma_1 - \sigma_2) / 3 = \sqrt{2} \cdot (\sigma_1 - \sigma_2) / 3 + \sqrt{2} \cdot \Delta\sigma_1 / 3$  and  $\tau_{oct} = \sqrt{2} \cdot \Delta\sigma_1 / 3 = 0.471 \Delta\sigma_1$ . From Fig.5,  $\Delta\sigma_1$  is 15, 56.7, 81.7, 106.7, 156.7 and 231.7 kPa, respectively. When  $\Delta\sigma_1 \leq 156.7 \text{ kPa}$ , creep is at stage (1) or (2), at these two creep period, there is no creep or creep is convergence and  $\Delta\tau_{oct} = 7.1, 26.7, 38.5, 50.3$  and  $73.8 \text{ kPa}$ , respectively, that is, when  $\Delta\tau_{oct} \leq 73.8 \text{ kPa}$ , it can be thought that the AGS system is stable. Of course, for brown silt clay,  $\Delta\tau_{oct}$  will be higher than that of mucky clay. The calculated  $\Delta\tau_{oct}$  of different option of anchor are tabulated in Table 2. From Table 2, we can know that for anchor option (1) and (2)-shallow foundation, stress level in grey mucky clay is much more greater than  $73.8 \text{ kPa}$ , the

mucky clay will be creep. For option (3) and (4)–the deep foundation, stress level in grey mucky clay is less than 73.8kPa. In brown silty clay (unimproved ground) is 102.2kPa, a little higher than 73.8kPa, but in brown silty the permitted  $\Delta\tau_{oct}$  is higher than 73.8kPa. In dark green silty clay,  $\Delta\tau_{oct}$  is very large, but this layer's creep behavior is not evidence or can be neglected.

Thus, it is manifested that the deep foundation option of anchor on Shanghai soft ground is rational.

## 6. CONCLUSIONS

This paper used the FEM and the creep data of soft mucky clay in Shanghai for analyzing possible stability of anchor-ground system. It is very useful for deciding the final selection of river cross project in OREP. It is confirmed that deep foundation anchor is much more stable and reliable than shallow foundation anchor. However, in this study only 2-dimensional FEM analysis and only creep property of soft mucky clay in Shanghai were used. There are some differences between theory and practice. If the suspension bridge option were put into practice, many detail and more precise studies would be further done.

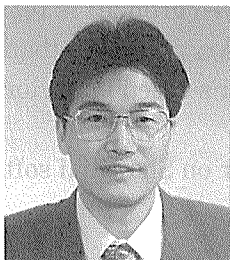
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